

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

Molecular validation of *Sarcodon quercinofibulatus*, a species of the *S. imbricatus* complex associated with Fagaceae, and notes on *Sarcodon*

This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/124757> since

Published version:

DOI:10.1007/s11557-012-0851-9

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)



UNIVERSITÀ DEGLI STUDI DI TORINO

This is an author version of the contribution published on:

Alfredo Vizzini , Matteo Carbone, Fabrizio Boccardo and Enrico Ercole

*“Molecular validation of **Sarcodon quercinofibulatus**, a species of the **S.imbricatus** complex associated with **Fagaceae**, and notes on **Sarcodon**”*

Mycological Progress - August 2013, Volume 12, Issue 3, pp 465-474, [10.1007/s11557-012-0851-9](https://doi.org/10.1007/s11557-012-0851-9)

The definitive version is available at:

La versione definitiva è disponibile alla URL:

[<http://link.springer.com/article/10.1007%2Fs11557-012-0851-9>]

Molecular validation of *Sarcodon quercinofibulatus*, a species of the *S. imbricatus* complex associated with Fagaceae, and notes on *Sarcodon*

Alfredo Vizzini , Matteo Carbone, Fabrizio Boccardo and Enrico Ercole

Abstract

Morphological and molecular phylogenetic analyses revealed that Italian and Mexican collections of an unknown *Sarcodon* species of the *S. imbricatus* complex associated with Fagaceae (*Castanea* and *Quercus*), were assignable to *Sarcodon quercinofibulatus*, a species recently described from Spain. The species, characterized by a light brown-hazelnut coloured pileus surface eventually breaking into large and coarse scales, was recognized as independent from *Sarcodon imbricatus* and *S. squamosus*. *S. aspratus*, usually synonymized with *S. imbricatus*, is a different species. *S. squamosus* collections from montane and Mediterranean pine woodlands were shown to be conspecific. Four sections of *Sarcodon* (*Sarcodon*, *Violacei*, *Squamiceps* and *Scabrosi*) established by Maas Geesteranus (Verh K ned Akad Wet III, 65: 1–127, 1975) only on morphological basis, are here confirmed as monophyletic.

Introduction

The genus *Sarcodon* Quél. ex P. Karst., typified by *Hydnum imbricatum* L., includes stipitate hydroid fungi characterized by fleshy basidiomata, a soft to firm, brittle and not zonated, never duplex context, a brown spore print, a monomitic hyphal system, generative hyphae often inflated with or without clamp-connections, and irregularly tuberculate spores (Maas Geesteranus 1956, 1971, 1975; Maas Geesteranus and Nannfeldt 1969; Baird 1984, 1986a, b; Harrison and Grund 1987; Jülich 1989; Stalpers 1993; Pegler et al. 1997; Strid 1997; Arnolds 2003). According to recent molecular analyses, *Sarcodon* belongs to the so called thelephoroid clade (=Thelephorales Corner ex Oberw. partim), together with other stipitate hydroid genera such as *Hydnellum* P. Karst., *Phellodon* P. Karst., *Bankera* Coker & Beers ex Pouzar; in these studies *Sarcodon* appears to be sister to *Hydnellum* (Bruns et al. 1998; Larsson et al. 2004; Binder et al. 2005).

Most of the *Sarcodon* species are distributed in the Northern temperate Hemisphere (Maas Geesteranus 1971, 1975; Baird 1986b; Stalpers 1993; Pegler et al. 1997), and are generally

regarded as ectomycorrhizal partners of a range of woody angiosperms and gymnosperms, particularly within Fagaceae and Pinaceae. Ectomycorrhizae formed by this group of fungi are poorly known: those produced by *S. imbricatus* and *S. leucopus* with *Picea abies* were described by Agerer (1991a, b) and Mleczko et al. (2011), and represent the only ones to have been well investigated in the genus to date. *Sarcodon* as well as the other stipitate hydroid fungi are extensively used in ecological-environmental research (Newton et al. 2002; Van der Linde et al. 2008, 2009, 2010; Hobbie and Agerer 2010; Lindman 2010; Mleczko et al. 2011). Basidiome production of these fungi has been declining in northern Europe and North America over the past few decades (Arnolds 1989, 2003, 2010; Otto 1990, 1992; Gulden and Hanssen 1992; Hrouda 1999a, b; Vesterholt et al. 2000; Walley and Verbeken 2000; Newton et al. 2002); it is suggested that this negative trend is correlated with habitat loss and increasing airborne nitrogenous eutrophication (Arnolds 1989, 2003, 2010; Vesterholt et al. 2000; Walley and Verbeken 2000). They are regarded as one of the most endangered groups of macrofungi in Europe (Hrouda 1999a, b, 2005a, b), resulting in their inclusion in European Red Data Lists (Walley and Verbeken 2000; Nitare 2006; Senn-Irlet et al. 2007; Hrouda 2005a, b).

Within *Sarcodon*, species identification relied primarily on the observation of a rather limited set of characters, such as presence/absence of clamp-connections, colour of the context in both pileus and stipe, arrangement of pileus surface, organoleptic features (smell and taste) and spore size (Harrison 1964; Maas Geesteranus and Nannfeldt 1969; Maas Geesteranus 1971, 1975; Harrison and Grund 1987; Baird 1986a, b; Stalpers 1993; Pegler et al. 1997; Strid 1997). Infrageneric partition of the European taxa of *Sarcodon* was addressed by Maas Geesteranus (1975), who recognized six sections, viz sect. *Sarcodon*, *Squamiceps* Maas Geest., *Scabrosi* Maas Geest., *Virescens* Maas Geest., *Violacei* Maas Geest. and *Velliceps* Maas Geest.; these sections were since then usually accepted by later authors. Sect. *Sarcodon* encompasses the clamp-bearing species having a clearly areolated fissured-scaly pileus, whitish to light brown context without green tinges and only rarely turning red vinaceous when cut, and absence of farinaceous smell and taste. In this section, *S. imbricatus* is a species traditionally defined by a fleshy, dark brown pileus, breaking up into large pronounced scales, erect in the centre of pileus but adpressed and flat on its margin, and deeply fissured between the scales; it is known from Europe, Asia and North America, usually associated with Pinaceae (*Picea* and *Pinus*, Maas Geesteranus 1971, 1975; Stalpers 1993; Pegler et al. 1997), but reported also

under hardwoods from North America (Coker and Beers 1951; Smith and Smith 1973; Baird 1986b).

Recently, Johannesson et al. (1999), based on morphological data and analysis of the ITS sequence distances and RFLP-patterns of several *S. imbricatus* collections from northern Europe, showed that specimens growing under *Picea abies* and those under *Pinus sylvestris* are different taxa, thus recognizing two species: *S. imbricatus* s.s. (under *Picea*) and *S. squamosus* (Schaeff.) Quél. (under *Pinus*). These two species mainly differ in the shape, colour and ornamentation of the pileus and host preferences; however, until the contribution of Johannesson et al., *Sarcodon squamosus* was for a long time been confused with *S. imbricatus*, even though the former *Hydnum squamosum* was described already in the eighteenth century by Schaeffer (1774). Because of the confusion, almost all specimens collected in the 20th century have been identified as *Sarcodon imbricatus*, and an exact identification of the old samples is difficult in some cases. Collections surely attributable to *S. squamosus* are those of Phillips (1981) and Pegler et al. (1997).

After Johannesson et al. (1999), *S. squamosus* was found under *Pinus sylvestris* and/or *P. nigra* in different European countries (Dickson 2000; Kotlaba and Pouzar 2000; Schafer 2000; Schmidt-Stohn 2001; Arnolds 2003; Hausknecht and Klofac 2004; Papoušek 2004; Hrouda 2005a, b; Della Maggiora 2007; Dollé et al. 2007; Shiryaev 2008; Kirk and Cooper 2009; Pérez-De-Gregorio et al. 2011), and under *P. pinaster* and *P. laricio* subsp. *calabrica* (*Pinus nigra* subsp. *laricio*) in Italy (Della Maggiora 2007).

Cifuentes (1996), Patiño-Conde et al. (2004) and Patiño-Conde (2006), based on morphological and molecular data, reported a *S. aff. imbricatus* from *Quercus* in *Quercus*-*Pinus* forests in Mexico, suggesting the existence of a second species close to *S. imbricatus*.

Recently, Pérez-De-Gregorio et al. (2011) established, on morphological basis only, the new species *Sarcodon quercinofibulatus* (as *S. quercinofibulatum*) for Spanish specimens differing from *S. imbricatus* and *S. squamosus* only for growing under a non-coniferous ectomycorrhizal host, *Quercus petraea*.

Hereafter we refer to the closely similar species *S. imbricatus*, *S. squamosus*, *S. quercinofibulatus* and *S. aff. imbricatus* as the *S. imbricatus* complex.

On account of morphological analysis and nrITS sequence data, the main aims of this study can be summarized as follows: i) to investigate the identity and the phylogenetic placement of several Italian collections of a *Sarcodon* species belonging to this complex characterized by a pale brown tomentose pileus, squamose only at maturity, and associated with *Castanea*

sativa; ii) to find out whether *S. squamosus* collections from Mediterranean pines are conspecific to those occurring in montane pine forests or not; iii) to test Maas Geesteranus' (1975) morphologically based taxonomy against molecular phylogenetic approach.

Materials and methods

Morphology

The description of the macroscopical features is based on fresh material. Micro-features are based on dried specimens, rehydrated in water or 5 % KOH, and then mounted in Congo red to observe the hymenium and pileipellis, and in water for spore dimensions and pigment localization. Spore size is expressed both as a range and mean value. Extreme measurements are indicated within parentheses; spore measurements include tubercles. The following abbreviations are used: [X, Y, Z] indicating that measurements were made on X spores, in Y samples from Z collections; Q = the spore quotient (length/width ratio); Qm = the average spore quotient. Author citations follow the Index Fungorum-Authors of Fungal Names (<http://www.indexfungorum.org/authorsoffungalnames.htm>). Colour terms in capital letters (e.g. Raw Sienna) are those of Ridgway (1912). Herbarium acronyms follow Thiers (2011) except that JC refers to the personal herbarium of J. Carbó.

DNA extraction, PCR amplification, and DNA sequencing

Genomic DNA was isolated from 1 mg of 12 herbarium specimens (Table 1) using the DNeasy Plant Mini Kit (Qiagen, Milan Italy). Universal primers ITS1f/ITS4 were used for the ITS region amplification (White et al. 1990; Gardes and Bruns 1993). Amplification reactions were performed in PE9700 thermal cycler (Perkin-Elmer, Applied Biosystems) in a 25 µl reaction mixture using the following final concentrations or total amounts: 5 ng DNA, 1 × PCR buffer (20 mM Tris/HCl pH 8.4, 50 mM KCl), 1 µM of each primer, 2.5 mM MgCl₂, 0.25 mM of each dNTP, 0.5 unit of Taq polymerase (Promega). The PCR program was as follows: 3 min at 95 °C for 1 cycle; 30 s at 94 °C, 45 s at 50 °C, 2 min at 72 °C for 35 cycles, 10 min at 72 °C for 1 cycle. PCR products were resolved on a 1.0 % agarose gel and visualized by staining with ethidium bromide. PCR products were purified and sequenced by MACROGEN Inc. (Seoul, Republic of Korea). Sequence assembly and editing were performed using Geneious v5.3 (Drummond et

al. 2010). The sequences are deposited in GenBank under the accession numbers given in Table 1.

Table 1

Sarcodon sequences newly generated for this study and associated GenBank accession numbers

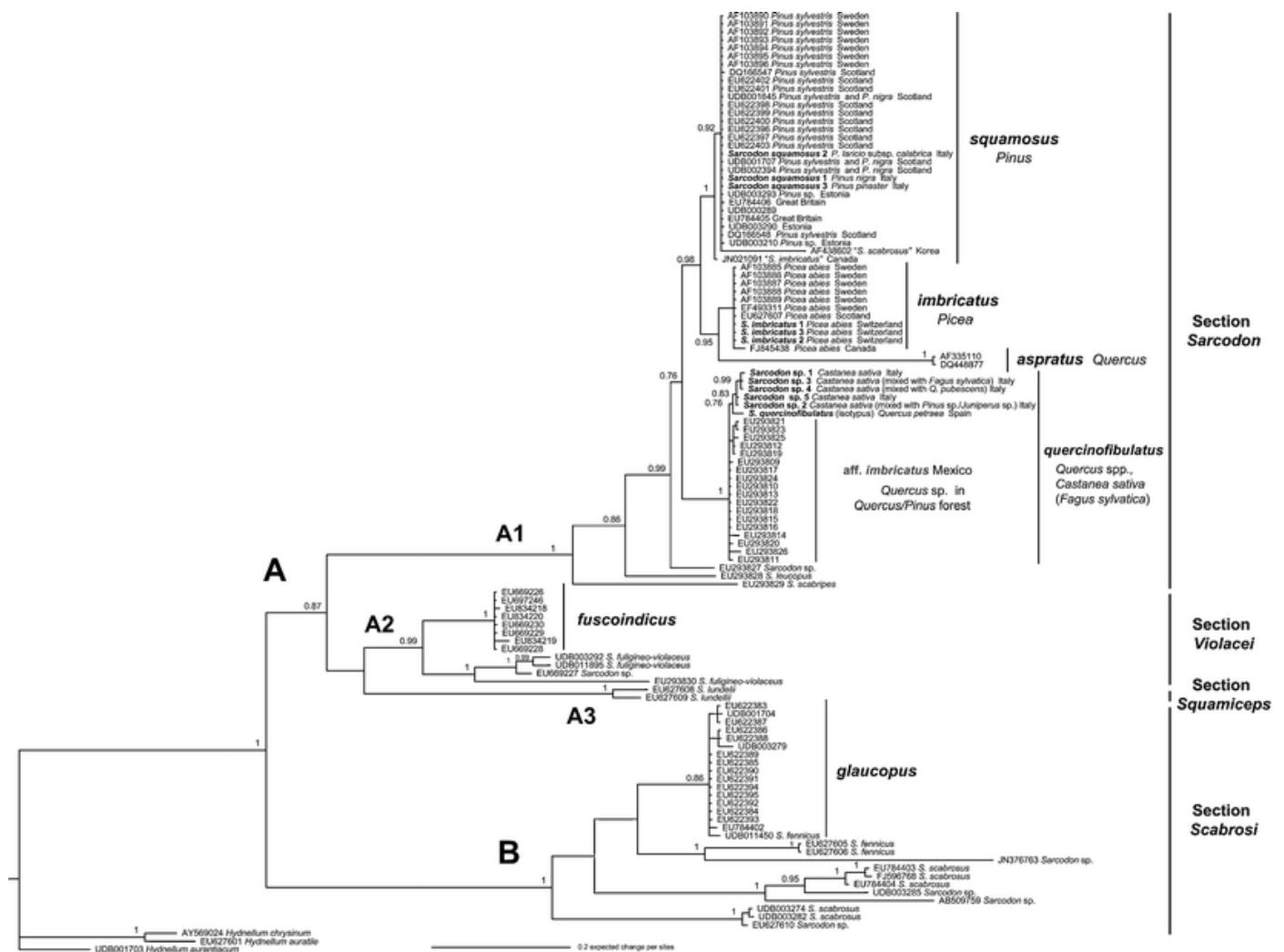
Species	Collection data	Herbarium no.	ITS GenBank acc. no.
S. imbricatus 1	Switzerland, Valais canton, Liddes, Chandonne, 18. 08. 2005, under Picea abies	MCVE 27380	JX271810
S. imbricatus 2	Switzerland, Ticino canton, Olivone, 14. 08. 2007, under Picea abies	MCVE 27381	JX271811
S. imbricatus 3	Switzerland, Ticino canton, Lucomagno, 25. 08. 2007, under Picea abies	MCVE 27382	JX271812
Sarcodon sp. 1	Italy, Liguria, Davagna (GE), Piancarnese, 18. 07. 2005, under Castanea sativa	MCVE 27374	JX271813
Sarcodon sp. 2	Italy, Liguria, Fontanigorda (GE), Casoni, 27. 09. 2005, under Castanea sativa (Castanea mixed forest with Pinus sp. and Juniperus sp.)	MCVE 27379	JX271814
Sarcodon sp. 3	Italy, Liguria, Fontanigorda (GE), Casoni, 14. 07. 2009, under Castanea sativa (Castanea mixed forest with Fagus sylvatica)	TUR-A 195698	JX271815
Sarcodon sp. 4	Italy, Lombardy, Varzi, Serra del Monte (PV), 21. 09. 2005, under Castanea sativa (Castanea mixed forest with Quercus pubescens)	TUR-A 195696	JX271816
Sarcodon sp. 5	Italy, Liguria, Savona, Sassello, 20. 07. 2009, under Castanea sativa	GDOR 1476	JX271817
S.	Spain, Girona, Puig Rodon, La Vall de Bianya,	JC-20090718.2	JX271818

Species	Collection data	Herbarium no.	ITS GenBank acc. no.
quercinofibulatus	18. 07. 2009, under Quercus petraea	(Isotypus)	
S. squamosus 1	Italy, Tuscany, Comano (MS), 07. 07. 1995, under Pinus nigra (P. nigra mixed forest with Castanea sativa)	TO AV 1195	JX271819
S. squamosus 2	Italy, Calabria, Gambarie (RC), 16. 10. 2003, under Pinus laricio subsp. calabrica	TO AV 258-S	JX271820
S. squamosus 3	Italy, Tuscany, Capannori (LU), Coselli, 25. 11. 2006, under Pinus pinaster	TO AV 623-S	JX271821

Sequence alignment and phylogenetic analysis

Sequences included in the phylogenetic analyses were either generated in this study (Table 1) or retrieved from GenBank (<http://www.ncbi.nlm.nih.gov/>) and UNITE (<http://unite.ut.ee/index.php?e=true>) databases. Multiple sequence alignments for ITS fragments were generated using MAFFT (Katoh et al. 2002) with default conditions for gap opening and gap extension penalty. The alignment was slightly edited using MEGA 5.0 (Tamura et al. 2011). Phylogenetic analysis was performed using the Bayesian Inference (BI) approach. The BI was performed with MrBayes 3.1.2 (Huelsenbeck and Ronquist 2001) with four incrementally heated simultaneous Monte Carlo Markov Chains (MCMC) run over 10 million generations, under GTR + Γ evolutionary model. Trees were sampled every 1,000 generations resulting in an overall sampling of 10,001 trees; the first 2,500 trees were discarded as “burn-in” (25 %). For the remaining trees, a majority rule consensus tree showing all compatible partitions was computed to obtain estimates for Bayesian Posterior Probabilities (BPP). Only BPP values over 0.75 are reported in the resulting tree (Fig. 1). Branch lengths were estimated as mean values over the sampled trees. Pairwise % identity values of ITS sequences (P%IV) were calculated using MEGA 5.0 (Tamura et al. 2011).

Fig. 1



Bayesian phylogram obtained from the ITS (ITS1-5.8S-ITS2) sequence alignment of *Sarcodon* spp. *Hydnellum auratile*, *H. aurantiacum* and *H. chrysinum* were used as outgroup taxa. BPP values over 0.75 are given above branches. Newly sequenced collections are in bold. Numbers (e.g. 1-5) refer to the *Sarcodon* collections reported in Table 1

Results

Molecular results

The amplification of the ITS regions was successful for the 12 specimens, yielding a PCR product of about 720 bp. The ITS data matrix comprises a total of 116 sequences (including 89 from GenBank and 15 from UNITE). The *Sarcodon atroviridis* sequence (EU293831) (*Sarcodon* sect. *Virescentes*) was not used since clearly of chimeric origin. This dataset is 882 base pairs long and contains 490 (55.6 %) variable sites. Of these, 402 (45.6 %) are parsimony-informative.

In the obtained Bayesian phylogram (Fig. 1), two major clades, A and B, were distinguished within *Sarcodon*. Clade A consists of three subclades (A1-A3). Clade A is supported by a BPP value of 0.87, while clade B by a BPP value of 1. A1, A2, A3 and B correspond quite well to the sections *Sarcodon*, *Violacei*, *Squamiceps* and *Scabrosi*, as traditionally delimited by Maas Geesteranus (1971, 1975).

Section *Sarcodon* (BPP = 1), the focus of the paper, encompasses six species; *S. squamosus*, *S. imbricatus*, *S. aspratus*, *S. quercinofibulatus*, *S. leucopus*, *Sarcodon* sp. and *S. scabripes*.

Our five sequences of *Sarcodon* collections from *Castanea sativa*, clustered together with the sequence of *S. quercinofibulatus* (isotypus, specimen from Spain) (P%IV = 99.4) and 18 sequences relating to *S. aff. imbricatus* from Mexico, forming a well supported monophyletic clade (BPP = 1). The pairwise % identity value of the 24 sequences of this clade is 98.6. European sequences differ from the Mexican ones only by one polymorphic site (one mutation) in position 599 of the total alignment (T instead of A). The *quercinofibulatus* clade is sister to a clade formed by *S. squamosus*, *S. imbricatus*, and *S. aspratus* (BPP = 0.98).

The three sequenced collections of *S. imbricatus* from Switzerland clustered with GenBank sequences of the same fungal species. This clade clustered sister to two *S. aspratus* sequences, forming a well supported clade (BPP = 0.95). The three sequenced collections of *S. squamosus* collected under Mediterranean pines (*P. pinaster* and *P. laricio* subsp. *calabrica*) clustered with GenBank and UNITE sequences from specimens collected under montane pines (*P. sylvestris* and *P. nigra*); the *squamosus* clade was supported by BPP of 1.

Taxonomy

Sarcodon quercinofibulatus Pérez-De-Greg., Macau & J. Carbó, Rev. Catal. Micol. 33: 26 (2011)
Figs. 2, 3, and 4



Fig. 2

Sarcodon quercinofibulatus. Macromorphological features. a Basidiomata (TUR-A 195698); b, c pileus surface and hymenophore (MCVE 2737); d, e scales (MCVE 27376 and TUR-A 195695). Photos by M. Carbone. Scale bars (a,c,d,e) 5 cm, (b) 10 cm



Fig. 3

Sarcodon quercinofibulatus. Basidiomata. Drawing by F. Boccardo (GDOR 1476)

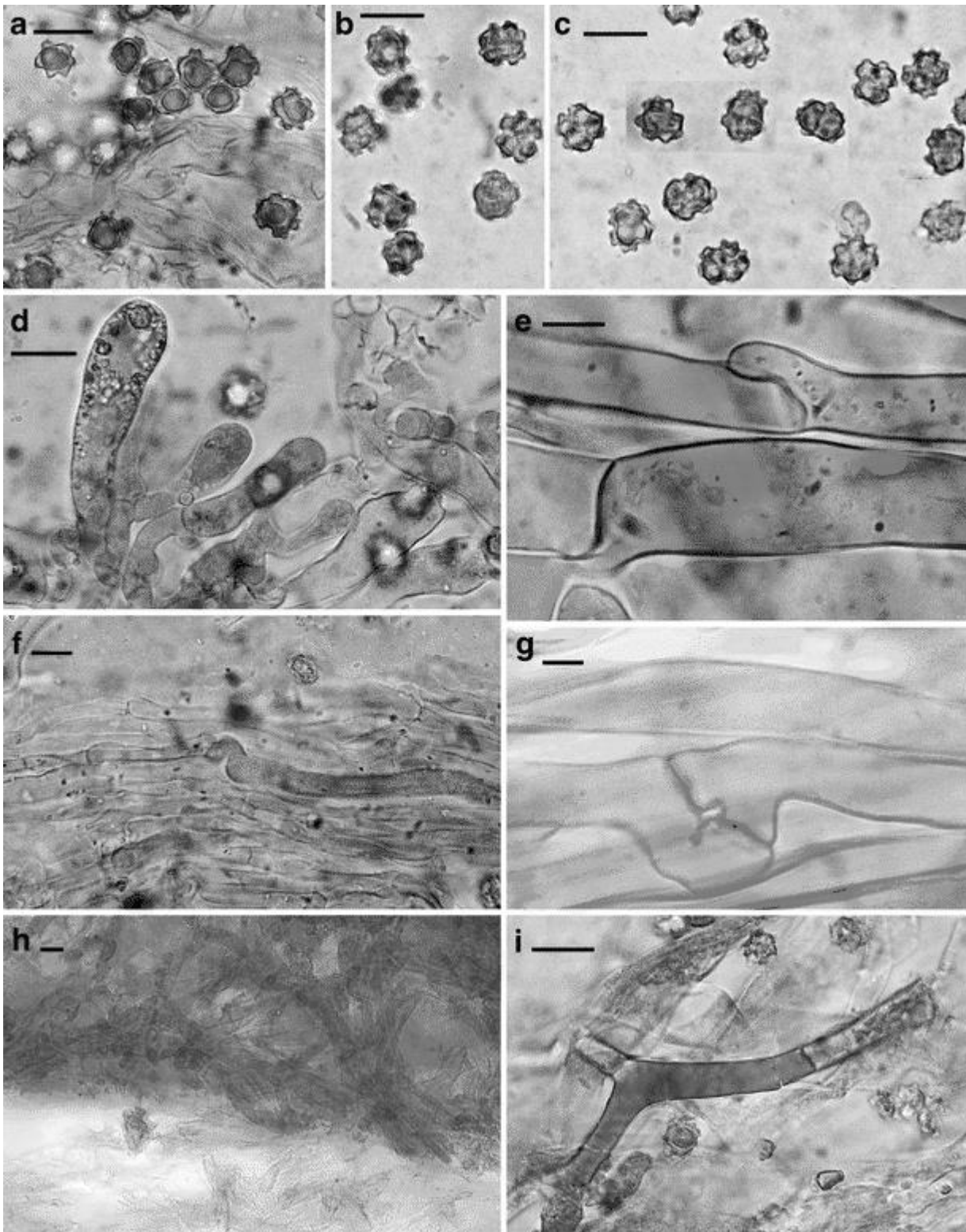


Fig. 4

Sarcodon quercinofibulatus. Micromorphological features (MCVE 27374). a-c Spores, d clamped hymenial elements, e clamp-connections in tramal hyphae, f hymenophoral trama with clamped thromboplerous hyphae, g medallion-type clamp connection, h pileipellis elements in water mount, i thromboplerous hyphae in the pileipellis. Photos by M. Carbone. Scale bars (a-i) 10 μ m

Macrocharacters Pileus up to 20(23) cm in diam., convex to plane, slightly to strongly umbilicate in age; surface hazelnut coloured, light brown (Mars Yellow, Raw Sienna, Ochraceous-Tawny), slightly darker (Buckthorn Brown, Sudan Brown, Hazel) in age; at first velutinous to very slightly floccose, then cracked by fissures forming scales arranged concentrically, mainly triangular to truncated pyramidal in shape, at first concolorous then darker than the background; tips not or only slightly pointed upward to definitely vertical in the centre in mature specimens; margin strongly incurved for long time, straight only in mature specimens; spines up to 1.2 cm long in large and over-mature specimens, adnate-subdecurrent to definitely decurrent on the stipe (both the types can occur on the same basidiome), whitish to grayish, then brownish; stipe up to 8 cm long and up to 2 cm wide, cream coloured, slightly darker to sub-concolorous with the pileus, central to slightly eccentric, cylindrical to sub-bulbose, covered by small aborted spines, often with curved base; context uniformly coloured in all parts, whitish to very pale brownish; taste mild but with a very slightly bitter aftertaste, barely appreciable on the back of the tongue after prolonged chewing; smell agreeable, reminiscent of liquorice in young basidiomes, stronger and more or less unpleasant in old specimens.

Microcharacters Spores [120, 6, 6], $(5.5-6-8(-8.3) \times (5.5-6-7(-7.6) \mu\text{m}$, on average $6.96 \times 6.38 \mu\text{m}$, $Q = 1-1.27$, $Q_m = 1.12$, globose to subglobose, brownish, irregular in outline due to the presence of numerous exsculptate to 3-pointed tubercles; basidia $(25-30-40(-45) \times 8-10 \mu\text{m}$, club-shaped, slender clavate, 4-spore, sterigmata up to $5 \mu\text{m}$ long, clamped; basidioles club-shaped, very numerous, clamped; cystidia absent; hymenophoral trama regular, composed of cylindrical hyphae, up to $6 \mu\text{m}$ wide, septate, thin-walled, hyaline, clamped, sometimes anastomosing; pileipellis composed of cylindrical hyphae, up to $10 \mu\text{m}$ wide, septate, thin-walled, clamped, brownish due to an epiparietal and intracellular pigment; suprapellis a cutis-subtrichoderm of prostrate hyphae with some bundles of hyphae rising upward; context consisting of hyphae up to $21(-24) \mu\text{m}$ wide, cylindrical, septate, branched, inflating, thin-walled, clamped; thromboplerous hyphae (=oleiferous hyphae sensu Cléménçon 2004) present; clamp connections abundant in all tissues; clamps of the medallion-type observed in the context.

Ecology and distribution Gregarious to subcespitose, on bare ground under broadleaved trees and strictly associated with Fagaceae: in Italy (Liguria and Lombardy) mainly under *Castanea sativa*, but also in mixed forests with *Quercus pubescens*, *Fagus sylvatica*, in one collection *Pinus* sp. and *Juniperus* sp. were nearby; in Spain collected under *Quercus petraea*, *Q. humilis*

and *Acer opalus*, and one collection under *Fagus sylvatica*; in Mexico, under *Quercus* sp. in *Quercus* and *Quercus/Pinus* forests.

Collections examined *Sarcodon quercinofibulatus*. ITALY- Liguria, Davagna (GE), loc. Piancarnese, 18. 07. 2005, many basidiomes under *Castanea sativa*, leg. M. Carbone (MCVE 27374); ibidem, in a different part of the same forest, 28. 07. 2005, leg. M. Carbone (MCVE 27375); ibidem, 02. 09 2005, leg. M. Carbone (MCVE 27376); ibidem, in a different part of the same forest, 05. 09. 2005, leg. M. Carbone (TUR-A 195695); ibidem, in a different part of the same forest, 22. 09. 2005, leg. M. Carbone (TUR-A 195697). Uscio (GE), 10. 09. 2005, two basidiomes under *Castanea sativa*, leg. M. Carbone (MCVE 27377). Recco (GE), 20. 08. 2006, one basidiome under *Castanea sativa*, leg. M. Carbone (MCVE 27378). Fontanigorda (GE), loc. Casoni, 27. 09. 2005, many basidiomes under *Castanea sativa* but with some *Pinus* sp. and *Juniperus* sp. in the surroundings, leg. M. Carbone (MCVE 27379); ibidem, many basidiomes, in the same forest but under *Castanea sativa* and *Fagus sylvatica*, 14. 07. 2009, leg. M. Carbone (TUR-A 195698). Lombardy, Varzi (PV), Serra del Monte, 21. 09. 2005, 3 basidiomes under *Castanea sativa* (*Castanea* mixed forest with *Quercus pubescens*), leg. M. Carbone (TUR-A 195696). Liguria, Savona, Sassello, 20. 07. 2009, under *Castanea sativa*, leg. F. Boccardo (GDOR 1476). SPAIN – Girona, La Vall de Bianya, Puig Rodon, 18. 07. 2009, under *Quercus petraea*, leg. J. Carbó, J. Galí, C. Miñarro, G. Mir, M.À. Pérez-De-Gregorio, and À. Torrent (JC-20090718.2, isotypus).

Additional collections examined *Sarcodon imbricatus*. SWITZERLAND - Valais canton, Liddes, loc. Chandonne, 18. 08. 2005, many basidiomes under *Picea abies*, leg. M. Carbone (MCVE 27380). Ticino canton, Olivone, 14. 08. 2007, many basidiomes under *Picea abies*, leg. M. Carbone (MCVE 27381). Ticino canton, Lucomagno, 25. 08. 2007, many basidiomes under *Picea abies*, leg. M. Carbone (MCVE 27382). *Sarcodon squamosus*. ITALY – Tuscany, Comano (MS), 07. 07. 1995, many basidiomes under *Pinus nigra* (*P. nigra* mixed forest with *Castanea sativa*), leg. Luciana Bonamini (TO AV1195); Calabria, Gambarie (RC), 16. 10. 2003, under *Pinus laricio* subsp. *calabrica*, leg. M. Della Maggiora (TO AV258-S); Tuscany, Capannori (LU), Coselli, 04. 12. 2005, under *Pinus pinaster*, leg. M. Della Maggiora (TO AV 623-S).

Discussion

Notes on the infrageneric classification of the genus *Sarcodon*

According to our phylogenetic analysis, two major clades are recognized within *Sarcodon* (Fig. 1): the clade A encompassing species with or without clamp-connections and

characterized by the absence of blue-green tinges at stipe base; clade B consisting of species without clamp-connections and with blue-green tinges at stipe base. Even if a more extensive sampling of *Sarcodon* species is needed for a comprehensive revision of the whole genus, our preliminary molecular data support the infrageneric *Sarcodon* classification established by Maas Geesteranus (1975). Four clades corresponding to four out of the six sections recognized by Maas Geesteranus were recovered: section *Sarcodon* (type species *S. imbricatus*, pileus fissurate to squamose, context without both blue-green and reddish violaceous tinges, odour not farinaceous, presence of abundant clamp connections), supported by BPP = 1, consists of *S. aspratus* (Berk.) S. Ito, *S. imbricatus*, *S. leucopus* (Pers.) Maas Geest. & Nannf., *S. quercinofibulatus*, *S. scabripes* (Peck) Banker, *Sarcodon* sp. and *S. squamosus*; section *Violacei* [type species *S. joeides* (Pass.) Bataille, context reddish pink, violaceous, odour farinaceous, clamp-connections very rare or absent], supported by BPP = 0.99, consists of *S. fuscoindicus* (K.A. Harrison) Maas Geest. and *S. fuligineo-violaceus* (Kalchbr.) Pat.; section *Squamiceps* (consisting only of the type species *S. lundellii*, pileus scaly-areolated, context whitish to brownish, odour usually farinaceous, absence of clamp connections); finally, section *Scabrosi* [type species *S. scabrosus* (Fr.) P. Karst., areolate pileus, bluish-green tinges at stipe base, absence of clamp-connections], supported by BPP = 1, consists of *S. glaucopus* Maas Geest. & Nannf., *S. fennicus* (P. Karst.) P. Karst. and *S. scabrosus*. Our phylogenetic analysis highlighted that the sequences of *S. scabrosus* from Genbank and UNITE databases form two distinct and well-supported clades, suggesting that *S. scabrosus*, as traditionally defined (e.g. Maas Geesteranus 1975; Baird 1986b; Stalpers 1993; Arnolds 2003), is polyphyletic and probably consists of two independent taxa.

No sequences were available for sect. *Velliceps* [type species *S. martioflavus* (Snell, K.A. Harrison & H.A.C. Jacks.) Maas Geest., pileus surface strongly velutinous, context whitish to brownish, odour farinaceous, clamp-connections absent]; for sect. *Virescentes* [type species *S. atroviridis* (Morgan) Banker, basidiome entirely turning olive green on drying, with or without clamp-connections] the only sequence present in GenBank is chimeric and it was not used for phylogenetic purposes.

***Sarcodon* collections of the *S. imbricatus* complex associated with Fagaceae**

Our specimens collected under *Castanea sativa* are clearly conspecific with *S. quercinofibulatus* from Spain associated with *Quercus petraea* (in one case with *Fagus sylvatica*) and with Mexican specimens collected under *Quercus* sp. in *Quercus*/*Pinus* forests

(Fig. 1). Spanish and Mexican collections show morphological features fitting well with the Italian ones (Cifuentes 1996; Patiño-Conde 2006; Pérez-De-Gregorio et al. 2011, and our observations). *S. quercinofibulatus* is proven to be a taxon independent from the *S. imbricatus*/*S. squamosus* species-pair. This species seems mainly associated with Fagaceae, and shows a disjoint distribution pattern, although this could be due to insufficient collection data. Only the presence of one polymorphic site in ITS sequences distinguishes European collections from Mexican ones (see Results) and this difference is probably attributable to geographical segregation.

As far as we know, the first account on the existence of this species in Italy (Liguria), under *Castanea sativa*, can be found in Orsino and Dameri (1989) under the name *Sarcodon imbricatus*. The authors stated (translated from Italian): “this species deserves further studies, because the specimens collected under chestnut trees show some differences from the typical collections fruiting under conifers in mountain areas”. Other records are also reported by Zotti and Orsino (2001), always as *S. imbricatus*. Our collections come from adjacent valleys, definitely sharing the same kind of habitat and climatic conditions. Coker and Beers (1951) and Baird (1986b) stated that in the eastern United States *S. imbricatus* is associated with frondose woods. Smith and Smith (1973) pointed out that it occurs throughout North America under both conifers and hardwoods. In the light of our present results we believe that further studies are required in order to ascertain if *S. quercinofibulatus* also occurs in broadleaved forests of northern and eastern United States.

S. imbricatus and *S. squamosus* are the two most similar species to *S. quercinofibulatus*. They appear to be quite identical under the microscope, but have a few morphological differences (Johannesson et al. 1999; Kotlaba and Pouzar 2000; Schafer 2000; Schmidt-Stohn 2001; Arnolds 2003; Della Maggiora 2007, and our observations): i) *S. imbricatus* s.s. is characterized by a brown pileus (paler than *S. squamosus*) with brown scales, a margin not remaining incurved for a long time, an always depressed, often infundibuliform or hollow centre with scales usually pointing almost straight upward; brown spines not decurrent and quite long; a stipe normally longer than the pileus diameter, cylindrical or with slightly bulbous base, not paler at the apex; a smell somewhat disagreeable, and a bitter taste; ii) *S. squamosus* is distinguished by a yellow-brown to vinaceous brown pileus with blackish brown scales, pileus margin remaining incurved, pileus centre not deeply depressed, scales usually smaller than *S. imbricatus* with those in the centre not or only slightly pointed upward; spines slightly decurrent, rather short and crowded, greyish, often with a greyish-

blue tint when fresh; stipe short, about the same as the pileus diameter or shorter, paler at the apex and narrowing at the base; smell aromatic-spicy, taste not bitter. The habitat seems to be an additional distinguishing feature: as pointed out by Johannesson et al. (1999) the former is associated with *Picea* on calcareous soil, and the latter with *Pinus* on acid soil. According to our analysis (Fig. 1) specimens of *S. squamosus* collected under montane pines (*P. sylvestris* and *P. nigra*) are genetically identical to those collected under Mediterranean pines (*P. pinaster* and *P. laricio*). *S. quercinofibulatus* differs from the *S. imbricatus*/*S. squamosus* pair only by a paler pileus, at first tomentose then squamose only at maturity, and for its association with *Fagaceae*. The *S. imbricatus* complex seems to be a case of host-driven speciation processes (Rochet et al. 2011).

S. aspratus from Japan, Korea and China (Kawagoe 1924; Imazeki et al. 1988; Huang 1998; Kim et al. 2002) at first was synonymized by Maas Geesteranus (1960, 1971) with *S. imbricatus*, and then considered an independent species close to *S. praestans* Maas Geest. from New Guinea (Maas Geesteranus 1974). According to our data (Fig. 1, P%IV = 94.1) *S. aspratus* is probably independent from *S. imbricatus*; it differs by having smaller pileal scales, a fragrant sweetish smell, and by growing under *Quercus* spp. (Kawagoe 1924; Maas Geesteranus 1971; Imazeki et al. 1988; Kim et al. 2002).

The presence of abundant clamp connections in all tissues is a striking feature which separates the *S. imbricatus* complex and the species belonging to *Sarcodon* sect. *Scabrosi* and *Sarcodon* sect. *Squamiceps* (Maas Geesteranus 1975). *S. scabrosus* is, in fact, very common in Italy under *Castanea sativa* but is microscopically unclamped and macroscopically it shows purplish hues on the pileus, pale grayish-bluish at the base of the stipe, farinaceous smell and very bitter taste. *Sarcodon regalis* Maas Geest. is another species recorded from *Castanea sativa* woods but it is very different macroscopically (Calledda and Carbone 2006). As pointed out by Pérez-De-Gregorio et al. (2011) the other known European species associated with broadleaved trees are unclamped. Among them, the only taxon macroscopically resembling *Sarcodon quercinofibulatus* is undoubtedly *S. underwoodii* Banker [incl. *Sarcodon radicans* Banker and *Sarcodon murrillii* Banker fide Maas Geesteranus and Nannfeldt (1969) and Baird (1986a, 1986b)]; for details about its distribution see also Banker (1906, 1913), Coker and Beers (1951), Hall and Stuntz (1972), Maas Geesteranus (1975), Stalpers (1993), Bessette et al. (1997), and more recently Dollé et al. (2007) concerning its presence in Europe. Nevertheless, all these above mentioned species show very different macroscopic (general habit, colours, smell and taste) and microscopic (spores size) features, as can be appreciated in Harrison

(1964), Maas Geesteranus (1971, 1974, 1975), McNabb (1971), Hall and Stuntz (1972), Baird (1984, 1986a, b), Breitenbach and Kränzlin (1986), Jülich (1989), Stalpers (1993) and Strid (1985, 1997).

Acknowledgments

We are grateful to J. Carbó (Girona, Spain) and M. Della Maggiora (Pieve di Compito-Capannori, Lucca, Italy) for sending herbarium specimens, to Samuele Voyron (University of Turin, Italy) for providing helpful technical assistance, and to Matteo Gelardi (Rome, Italy) and Caroline Hobart (Sheffield, U.K.) for improving the English text. Lastly, thanks to J. Vauras (TUR-A Herbarium, Turku, Finland) and G. Robich (MCVE Herbarium, Venice, Italy) for housing many of the studied collections.

References

- Agerer R (1991a) Ectomycorrhizae of *Sarcodon imbricatus* on Norway spruce and their chlamydospores. *Mycorrhiza* 1:21–30CrossRef
- Agerer R (1991b) *Sarcodon imbricatus*. In: Agerer R (ed.) *Colour Atlas of Ectomycorrhizae*, Einhorn, Schwäbisch Gmünd, plate 66
- Arnolds E (1989) Former and present distribution of stipitate hydneous fungi (Basidiomycetes) in the Netherlands. *Nova Hedwigia* 48:107–142
- Arnolds E (2003) De stekelzwammen en pruikzwammen van Nederland en België. *Coolia* 46(3), suppl: 1–96
- Arnolds E (2010) The fate of hydroid fungi in The Netherlands and Northwestern Europe. *Fungal Ecol* 3:81–88CrossRef
- Baird RE (1984) Study of the stipitate hydnums of the southern Appalachian Mountains. Genera: *Bankera*, *Hydnellum*, *Phellodon*, *Sarcodon*. Ph.D. dissertation, University of Tennessee, Knoxville
- Baird RE (1986a) Type studies of North American and other related taxa of stipitate hydnums: Genera *Bankera*, *Hydnellum*, *Phellodon*, *Sarcodon*. *Bibl Mycol* 103:1–89
- Baird RE (1986b) Study of the stipitate hydnums of Appalachian mountains. *Bibl Mycol* 104:1–156
- Banker HJ (1906) A contribution to a revision of the North American Hydneaceae. *Mem Torr Bot Club* 12(2):99–194
- Banker HJ (1913) Type studies in the Hydneaceae III. The genus *Sarcodon*. *Mycologia* 5:12–17CrossRef

- Bessette AE, Bessette AR, Fischer DW (1997) Mushrooms of Northeastern North America. Syracuse University Press, Syracuse
- Binder M, Hibbett DS, Larsson K-H, Larsson E, Langer E, Langer G (2005) The phylogenetic distribution of resupinate forms across the major clades of mushroom-forming fungi (Homobasidiomycetes). *Syst Biodivers* 3(2):113–157CrossRef
- Breitenbach J, Kränzlin K (1986) Champignon de Suisse Vol. 2. Verlag Mykologia, Luzern
- Bruns TD, Szaro TM, Gardes M, Cullings KW, Pan JJ, Taylor DL, Horton DR, Kretzer A, Garbelotto M, Li Y (1998) A sequence database for the identification of ectomycorrhizal basidiomycetes by phylogenetic analysis. *Mol Ecol* 7:257–272CrossRef
- Calledda F, Carbone M (2006) Una “idnacea” non comune in Italia: *Sarcodon regalis*. *Pagine di Micologia* 26:27–30
- Cifuentes BJ (1996) Estudio taxonómico de los generos hidnoides estipitados (Fungi: Aphyllophorales) en México. Tesis de Doctorado en Ciencias (Biología). Fac. De Ciencias, UNAM, Mexico DF
- Cléménçon H (2004) Cytology and plectology of the Hymenomycetes. *Bibl Mycol* 199:1–488
- Coker WM, Beers AH (1951) The stipitate hydnums of the eastern United States. University of North Carolina Press, Chapel Hill
- Della Maggiora M (2007) *Sarcodon squamosus* una specie comune ma poco conosciuta. *Riv Micol* 50(2):127–137
- Dickson G (2000) A field key to British non-resupinate hydroid fungi. *Field Mycol* 1(3):99–104CrossRef
- Dollé B, Moingeon JM, Sugny D (2007) *Sarcodon underwoodii*, un taxon signalé pour la première fois en France. *Bull Soc Mycol Fr* 123(1):29–40
- Drummond AJ, Ashton B, Buxton S, Cheung M, Cooper A, Duran C, Field M, Heled J, Kearse M, Markowitz S, Moir R, Stones-Havas S, Sturrock S, Thierer T, Wilson A (2010) Geneious v5.3. Available from <http://www.geneious.com/>
- Gardes M, Bruns TD (1993) ITS primers with enhanced specificity for basidiomycetes – application to the identification of mycorrhizae and rusts. *Mol Ecol* 2:113–118PubMedCrossRef
- Gulden G, Hanssen EW (1992) Distribution and ecology of stipitate hydneous fungi in Norway, with special reference to the question of decline. *Sommerfeltia* 13:1–58
- Hall D, Stuntz DE (1972) Pileate Hydneae of the Puget Sound Area. II. Brown-Spored Genera: *Hydnum*. *Mycologia* 64(1):15–37CrossRef

- Harrison KA (1964) New or little known North American stipitate hydnums. *Can J Bot* 42(9):1205–1233CrossRef
- Harrison KA, Grund DW (1987) Preliminary keys to the terrestrial stipitate hydnums of North America. *Mycotaxon* 28(2):419–426
- Hausknecht A, Klofac W (2004) Ergebnisse des Mykologisches Arbeitstreffens in Horitschon (Burgenland) im September/Oktober 2001. *Österr Z Mykol* 13:237–265
- Hobbie EA, Agerer R (2010) Nitrogen isotopes in ectomycorrhizal sporocarps correspond to belowground exploration types. *Plant Soil* 327(1–2):71–83CrossRef
- Hrouda P (1999a) Hydneous fungi of the Czech Republic and Slovakia. *Czech Mycol* 51:99–155
- Hrouda P (1999b) Hydneous fungi – changes in their occurrence and possible causes. In: Jankovský L, Krejčíř R, Antonín V (eds) *Houby a les (sborník referátu)*. MZLU, Brno, pp 53–56
- Hrouda P (2005a) Bankeraceae in Central Europe. 1. *Czech Mycol* 57(1–2):57–78
- Hrouda P (2005b) Bankeraceae in Central Europe. 2. *Czech Mycol* 57(3–4):279–297
- Huang N-L (1998) Colored illustration of macrofungi (mushrooms) of China. China Agricultural Press, Beijing
- Huelsenbeck JP, Ronquist F (2001) MrBayes: Bayesian inference of phylogeny. *Bioinformatics* 17:754–755PubMedCrossRef
- Imazeki R, Otani Y, Hongo T (1988) *Fungi of Japan*. Yama-kei Publ, Tokyo
- Johannesson H, Ryman S, Lundmark H, Danell E (1999) *Sarcodon imbricatus* and *Sarcodon squamosus* - two confused species. *Mycol Res* 103(11):1447–1452CrossRef
- Jülich W (1989) *Guida alla determinazione dei funghi vol. 2*. Edizioni Saturnia, Trento
- Katoh K, Misawa K, Kuma K, Miyata T (2002) MAFFT: a novel method for rapid multiple sequence alignment based on fast Fourier transform. *Nucl Acids Res* 30:3059–3066PubMedCrossRef
- Kawagoe S (1924) The market fungi of Japan. *Trans Brit mycol Soc* 10:201–206CrossRef
- Kim HE, Koo CD, Kim JS, Park JI, Shin WS, Shin CS (2002) Ecological characteristics of below-ground ectomycorrhizal colony of *Sarcodon aspratus* in oak tree stands. *J Kor For Soc* 91:457–464
- Kirk P, Cooper J (2009) The GB Checklist of Fungal Names. <http://www.fieldmycology.net/GBCHKLST/gbchklst.htm>
- Kotlaba F, Pouzar Z (2000) Přehlížený druh našich lošáků - *Sarcodon squamosus*. *Mykol Listy, Praha* 74:5–7

- Larsson K-H, Larsson E, Kõljalg U (2004) High phylogenetic diversity among corticioid Homobasidiomycetes. *Mycol Res* 108:983–1002PubMedCrossRef
- Lindman J (2010) Evaluation of an ectomycorrhizal macrofungi as an indicator species of high conservation value pine-heath forests in northern Sweden. Master degree thesis in Biology, Department of Forest Ecology and Management, Faculty of Forest Sciences, SLU, Umeå
- Maas Geesteranus RA (1956) The stipitate Hydnums of the Netherlands. I. *Sarcodon* P. Karst. *Fungus* 26:44–60
- Maas Geesteranus RA (1960) Notes on hydnums. *Persoonia* 1:341–384
- Maas Geesteranus RA (1971) Hydnceous fungi of the eastern old world. *Verh K ned Akad Wet II* 60(3):1–176
- Maas Geesteranus RA (1974) Hydnceous fungi of the eastern Old World. Supplement. *Proc K Ned Akad Wet, Sect C* 77:477–495
- Maas Geesteranus RA (1975) Die terrestrischen Stachelpilze Europas. *Verh K ned Akad Wet III* 65:1–127
- Maas Geesteranus RA, Nannfeldt JA (1969) The genus *Sarcodon* in Sweden in the light of recent investigations. *Svensk Bot Tidskr* 63(4):401–440
- McNabb RFR (1971) Some new and revised taxa of New Zealand Basidiomycetes (Fungi). *N Z J Bot* 9:355–370CrossRef
- Mleczko P, Zubek S, Kozak M (2011) Description of ectomycorrhiza and a new Central European locality of the rare hydroid species *Sarcodon leucopus* (Pers.) Maas Geest. et Nannf. (Thelephorales, Basidiomycota). *Nova Hedwigia* 92(1–2):257–272CrossRef
- Newton AC, Holden E, Davy LM, Ward SD, Fleming LV, Watling R (2002) Status and distribution of stipitate hydroid fungi in Scottish coniferous forests. *Biol Conserv* 107(2):181–192CrossRef
- Nitare J (2006) Åtgärdsprogram för bevarande av rödlistade fjälltaggsvampar (*Sarcodon*). Naturvårdsverket, Stockholm, Rapport 5609
- Orsino F, Dameri RM (1989) Ricerca sulla flora della Liguria. 2. I macromiceti die castagneti delle alte Valli Scrivia e Polcevera (Apennino ligure). *Webbia* 43(2):355–386CrossRef
- Otto P (1990) Die terrestrischen Stachelpilze der DDR-Taxonomie, Ökologie, Verbreitung und Rückgang. Dissertation, Martin-Luther-Universität, Halle-Wittenberg
- Otto P (1992) Verbreitung und Rückgang der terrestrischen Stachelpilze Ostdeutschlands. *Gleditschia* 20:153–202
- Papoušek T (2004) Velký fotoatlas hub z jižních Čech. České Budějovice

- Patiño-Conde V. (2006) Relaciones filogenéticas del complejo *Sarcodon imbricatus*-*S. squamosus*. Maestría en Ciencias Biológicas (Sistemática). Facultad des Ciencias. Universidad Nacional Autónoma de México.
- Patiño-Conde V, Cifuentes J, González D, Magallón S, León-Regagnon V (2004) Taxonomic boundaries of *Sarcodon imbricatus* sensu lato from Mexico. Annual Meeting, Mycological Society of America – poster. Asheville N.C., July 15-21
- Pegler DN, Roberts PJ, Spooner BM (1997) British chanterelles and tooth fungi. Royal Botanical Gardens KEW, London
- Pérez-De-Gregorio MÀ, Macau N, Carbó J (2011) *Sarcodon quercinofibulatum*, una nueva especie del género con hifas fibulíferas. *Rev Catal Micol* 33:25–30
- Phillips R (1981) Mushrooms and other fungi of Great Britain and Europe. Pan Books, London
- Ridgway R (1912) Color standards and color nomenclature. Washington, D.C., published privately (by the author)
- Rochet J, Moreau P-A, Manzi S, Gardes M (2011) Comparative phylogenies and host specialization in the alder ectomycorrhizal fungi *Alnicola*, *Alpova* and *Lactarius* (Basidiomycota) in Europe. *BMC Evol Biol* 11:40PubMedCrossRef
- Schaeffer JC (1774). *Fungorum qui in Bavaria et Palatinatu circa Ratisbonam nascuntur*. Vol. IV, Regensburg
- Schafer D (2000) Dyeing to resurrect an old species? *Field Mycol* 1(2):42–43CrossRef
- Schmidt-Stohn G (2001) *Sarcodon imbricatus* und *S. squamosus* – zwei vermischte Arten. *Boletus* 24(1):48–53
- Senn-Irlet B, Bieri G, Egli S (2007) Lista Rossa dei macromiceti minacciati in Svizzera. Ed. Ufficio federale dell’ambiente, Berna e WSL, Birmensdorf. Pratica ambientale n. 0718
- Shiryaev A (2008) Diversity and distribution of thelephoroid fungi (Basidiomycota, Thelephorales) in the Sverdlovsk region, Russia. *Folia Cryptog Estonica* 44:131–141
- Smith AH, Smith HV (1973) How to know the non-gilled mushrooms. Wm. C. Brown Company, Iowa
- Stalpers JA (1993) The Aphyllophoraceous fungi I: keys to the species of the Thelephorales. *Stud Mycol* 35:3–168
- Strid Å (1985) Svenska taggsvampar 6. Släktet *Sarcodon*. *Jordstjärnan* 6:5–10
- Strid Å (1997) *Sarcodon* P. Karst. In: Hansen L, Knudsen H (eds) *Nordic macromycetes*, vol 3. Nordsvamp, Copenhagen, pp 313–315

- Tamura K, Peterson D, Peterson N, Stecher G, Nei M, Kumar S (2011) MEGA5: molecular evolutionary genetics analysis using maximum likelihood, evolutionary distance, and maximum parsimony methods. *Mol Biol Evol* 28:2731–2739PubMedCrossRef
- Thiers B (2011) [continuously updated] Index Herbariorum: A global directory of public herbaria and associated staff. New York Botanical Garden's Virtual Herbarium. <http://sweetgum.nybg.org/ih/>
- Van der Linde S, Alexander IJ, Anderson IC (2008) A PCR-based method for detecting the mycelia of stipitate hydroid fungi in soil. *J Microbiol Methods* 75:40–46PubMedCrossRef
- Van der Linde S, Alexander IJ, Anderson IC (2009) Spatial distribution of sporocarps of stipitate hydroid fungi and their belowground mycelium. *FEMS Microbiol Ecol* 69(3):344–352PubMedCrossRef
- Van der Linde S, Alexander IJ, Anderson IC (2010) Do stipitate hydroid fungi have the ability to colonise new native pine forest? *Fungal Ecol* 3:89–93CrossRef
- Vesterholt J, Asman W, Christensen M (2000) Nitrogen deposition and decline of fungi on poor and sandy soils. *Svampe* 42:53–60
- Walley R, Verbeken A (2000) Een gedocumenteerde Rode Lijst van enkele groepen paddestoelen (macrofungi) in Vlaanderen. Instituut voor Natuurbehoud, Brussel
- White TJ, Bruns TD, Lee S, Taylor J (1990) Amplification and direct sequencing of fungal ribosomal RNA genes for phylogenetics. In: Innis MA, Gelfand D, Sninsky J, White T (eds) *PCR Protocols, a guide to methods and applications*. Academic, Orlando, pp 315–322
- Zotti M, Orsino F (2001) The check-list of macrofungi in Liguria. *Fl Medit* 11:115–294